

- Phillips, O. M. (1985). " Spectral and statistical properties of the equilibrium range in wind-generated gravity waves." J.Fluid Mech., 156, 505-531.
- Tayfun, M. A. (1986). " On narrow-band representation of ocean waves." J. Geophys. Res., 91(C6), 7743-7759.
- Tayfun, M. A., and Lo, J.-M. (1990). " Nonlinear effects on wave envelope and phase." J. Waterw., Port, Coastl., and Oc. Engrg., ASCE, 116(1), 79-100.
- Tayfun, M. A. (1990). " High-wave-number/frequency attenuation of wind-wave spectra." J. Waterw., Port, Coastl., and Oc. Engrg., ASCE, 116(3), 381-398.

## MODELING BOTTOM FRICTION IN WIND-WAVE MODELS <sup>1</sup>

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### ABSTRACT

Effects of bottom friction in wind-wave models are investigated, with an emphasis on wave-induced bottom roughnesses (moveable-bed effects). A state-of-the-art bottom friction model is defined, based on literature. An analysis of this model indicates that, initial ripple-formation is important for swell propagation, but that moveable-bed effects are less important for depth-limited wind-seas. The small spatial decay scales associated with swell call for a sub-grid approach in (large-scale) numerical models. A sub-grid model is developed and applied successfully to swell and wind-sea cases, removing (unrealistically) large effects of sediment parameters in the later cases. Finally, implications for wave observations and sediment transport are discussed briefly.

### 1 Introduction

Wind-waves in oceans and shelf seas are generally described with their surface elevation ("energy") spectra, the development of which is described using a spectral balance equation. In shallow water wave-bottom interactions become a potentially important source term in the wave energy balance. An early review of such source terms is given by Shemdin et al. (1978), who consider percolation, bottom motion, bottom-friction and scattering of wave energy. For sandy bottoms, as found in many shelf seas, Shemdin et al. (1978) expect

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bottom-friction to be dominant, in particular when the near-bottom wave motion is sufficiently strong to generate sediment transport and corresponding bed-forms (ripple-formation). In fact, only ripple-formation can explain the large range of friction factors observed for swell in nature [Shemdin et al. (1978)], and the large friction factors for laboratory experiments with irregular waves [Madsen and Rosengaus (1988), Madsen et al. (1990)]. However, in modeling bottom friction in numerical wind-wave models, the attention is usually focussed on hydrodynamic aspects of the source term, assuming that the physical bottom roughness is known [e.g., Cavaleri and Lionello (1990), Weber (1991a,b)]. To the knowledge of the present author, efforts to explicitly model moveable-bed bottom roughnesses are presented by Graber and Madsen (1988) and Tolman (1989) only.

The present study seeks to investigate bottom friction in wind-wave models with an emphasis on moveable-bed effects. To this end, a state-of-the-art model is defined in section 2. In section 3, this model is analyzed with respect to occurrence of roughness regimes and space scales of decay for bottom friction. It is shown that typical swell can be associated to both smooth beds and wave-induced sand ripples, and that depth-limited wind-seas are generally associated with washed-out ripples and sheet-flow roughness. It is shown, that initial ripple-formation might result in preferred wave heights for swell propagation in shelf seas away from the coast, when bottom slopes are small. The corresponding decay scales [O(10 km)], call for a sub-grid approach in numerical models. A sub-grid model is briefly described in section 4, and applied successfully to swell propagation and depth-limited wind-seas in section 5. The wind-sea cases furthermore indicate, that a sub-grid approach is essential to avoid unrealistically strong dependencies of depth-limited wave heights on sediment parameters. Finally, the present results and implications for wave observations and sediment transport studies are discussed briefly in section 6. Note that the presentation and discussion of results has to be cursory due to space limitations. The results of this study will be presented in full elsewhere.

## 2 A local bottom friction model

In the present study, the hydrodynamic bottom friction source term of Madsen et al. (1988) is used. This model is selected because (i) it is a simple model, yet it explicitly depends on the Nikuradse equivalent sand grain roughness  $k_N$  and (ii) for consistency with the roughness model below. This model relates the source term  $S_1$  to the surface elevation spectrum  $F$  using a drag-law approach (the subscript 1 denoting "local" for later comparison with a sub-grid model)

$$S_1 = -f_w u_r \frac{\omega^2}{2g \sinh^2 kd} F, \quad (1)$$

$$f_w = \frac{0.08}{\text{Kei}^2(2\sqrt{\zeta_0}) + \text{Kei}^2(2\sqrt{\zeta_0})}, \quad (2)$$

$$\zeta_0 = \frac{1}{21.2 \kappa \sqrt{f_w}} \frac{k_N}{a_r}, \quad (3)$$

$$u_r = \left\{ \int \frac{2\omega^2}{\sinh^2 kd} F \right\}^{\frac{1}{2}}, \quad a_r = \left\{ \int \frac{2}{\sinh^2 kd} F \right\}^{\frac{1}{2}}, \quad (4)$$

where  $\omega = 2\pi f$  is the radian frequency,  $d$  is the depth,  $f_w$  is the wave friction factor,  $\kappa$  is the Von Kármán constant,  $\text{Kei}$  and  $\text{Kei}$  are Kelvin functions of the zeroth order and  $u_r$  and  $a_r$  are the representative near-bottom orbital velocity and amplitude, obtained by integration over  $F$ . Note that  $f_w$  is a function of  $k_N/a_r$  only, and that  $f_w$  is constant for  $k_N/a_r > 1$  ( $f_w = 0.236$  in the present model). Note furthermore, that this model shows a relation between the roughness  $k_N$  and Weber's "dissipation coefficient"  $C \equiv f_w u_r$ , similar to that of the most advanced eddy viscosity models of Weber (1991a), the main differences being a moderate intra-spectral variation of  $C$  which is neglected here and a systematic difference between friction factors for identical roughnesses  $k_N$ , which could be interpreted as a different definition of the bottom roughness (figures not presented here).

Grant and Madsen (1982, henceforth denoted as GM) developed a semi-empirical moveable-bed roughness model based on observations for monochromatic waves. This model relates  $k_N$  to the Shields number  $\psi$ , which is defined here as [Cf. Madsen et al. (1990)]

$$\psi = \frac{f_w u_r^2}{2(g-1)gD}, \quad (5)$$

where  $s$  is the relative density of the sediment compared to water (2.65 for quartz sands),  $D$  is a representative grain diameter and the prime indicates that the friction factor is based on skin friction, i.e., using  $k_N = D$  in Eq. (3). The